

# Rapid cooling of neutron star in Cassiopeia A and $r$ -mode damping in the core

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## ABSTRACT

We proposed alternative explanation to the rapid cooling of neutron star in Cas A. It is suggested that the star is experiencing the recovery period following the  $r$ -mode heating process, assuming the star is differentially rotating. Like the neutron-superfluidity-triggering model, our model predicts the rapid cooling will continue for several decades. However, the behavior of the two models has slight differences, and they might be distinguished by observations in the near future.

*Subject headings:* supernovae: individual(Cassiopeia A) — stars: neutron — stars: evolution

## 1. Introduction

The neutron star in Cassiopeia A (Cas A) is one of the most important isolated neutron stars (NSs) in testing the thermal evolution theory of NS because both its age and surface temperature are reliably estimated:  $t \approx 330 \pm 20$  yr (Fesen et al. 2006) and  $T_s \sim 2 \times 10^6$  K (Ho & Heinke 2009). The importance of Cas A NS was greatly enhanced recently, as Ho & Heinke (2010) found a steady decline of  $T_s$  by about 4% by analyzing the 10 year *Chandra* observations of it, and the new observational data reported by Shternin et al. (2011) confirms and extends this cooling trend (see table 1 in Shternin et al. 2011).

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Page et al. (2011) and Sheternin et al. (2011) suggested that the observed decreasing of the surface temperature of Cas A NS is difficult to explain by the cooling theory in spite of considering the triplet-state neutron superfluidity: this cooling rate is much larger than expected from the standard modified Urca process; and it is not likely due to the crust-core relaxation, which is supposed to last for typically  $\leq 100$  yr (e.g., Lattimer et al. 1994; Yakovlev et al. 2010). They also found that if this rapid cooling is triggered by ”breaking and formation of Cooper pairs (PBF)” neutrino-emission process, the cooling data may constrain the critical temperature of the triplet-state neutron superfluidity to several times of  $10^8$ K.

In this *Letter*, we present an alternative explanation to the rapid cooling of Cas A NS, which suggests that the star is experiencing the recovery period when the  $r$ -mode heating process is over. In the next section, we discuss the  $r$ -mode heating mechanism during the thermal evolution of neutron stars. After that, our explanation of the cooling data of Cas A NS is given. The last section is our conclusions and discussions.

## 2. $R$ -mode heating in neutron stars

Ever since 1998,  $r$ -mode instability is extensively studied in compact stars as the most important gravitational radiation-driven Chandrasekhar-Fridman-Schutz instability (Andersson 1998; Friedman & Morsink 1998), it is believed that it determines the spin limit of compact stars and the gravitational wave emitted during the instable process of the star can be detected by the new generation of gravitational-wave detectors (Andersson & Kokkotas 2001). However, The role of the  $r$ -mode dissipation for the thermal evolution of compact stars has long been ignored because the heating effect due to the  $r$ -mode dissipation is supposed to exist only in the first several decades of the newly born neutron stars (Watts & Andersson 2002). Nevertheless, Zheng et al. (2006) found that for strange stars made of strange quark matter (SQM), the  $r$ -mode heating effect can last for even  $10^7$  years.

In fact, there exists a saturated amplitude for  $r$ -modes in compact stars during the instable process. Since the saturated amplitude is determined by the nonlinear effects, it is usually put into the model artificially (Owen et al. 1998; Ho & Lai 2000). Many efforts have been paid to the study of the nonlinear effects to give a saturated  $r$ -mode amplitude naturally (e.g., Schenk et al. 2002; Arras et al. 2003; Brink et al. 2004, 2005). As an important nonlinear effect, differential rotation induced by  $r$ -modes was studied extensively (Rezzolla et al. 2000, 2001a,b; Stergioulas & Font 2001; Lindblom et al. 2001, Sá 2004). Among which Sá (2004) and Sá & Tomé (2005, 2006) solved the fluid equations within nonlinear theory up to the second order in the mode amplitude and described the differential rotation analytically. By doing so, they obtained a saturated amplitude of  $r$ -modes self-consistently,

which depends upon the parameter that describing the initial condition of the differential rotation.

Using the model developed by Sá (2004) and Sá & Tomé (2005, 2006), Yu et al. (2009) investigated the long-term spin and thermal evolution of isolated NSs under the influence of the differential rotation, and pointed out that the stars can keep nearly a constant temperature for over a thousand years since the differential rotation significantly prolongs the duration of  $r$ -modes. The detailed study by Yang et al. (2010) found that the heating effect of the prolonged  $r$ -modes enables us to explain the two young and hot pulsar’s (PSR B0531+21 and RX J0822-4300) temperature data with NS model composed of simple  $npe$  matter, without the inclusion of superfluidity or exotic particles.

Both in the thermal evolution curves of fig.2 in Yu et al. (2009) and fig.1 in Yang et al. (2010), It can be easily found that a rapid cooling period emerges immediately after the  $r$ -mode heating process is switched off. Therefore, we try to explain the observed rapid cooling of Cas A NS following Yang et al. (2010) in the next section.

### 3. The results

In order to simulate the thermal evolution, the thermal evolution equation of NS must be solved numerically coupling with the equations of the  $r$ -mode evolution and the spin evolution of the star(see equations (13), (14) and (15) of Yang et al. (2010)). We take the initial temperature  $T_0 = 10^{10}\text{K}$ , the initial  $r$ -mode amplitude  $\alpha_0 = 10^{-6}$  and the initial angular velocity  $\Omega_0 = \frac{2}{3}\sqrt{\pi G \bar{\rho}}$ .

In our simulation, we took the magnetic field as  $B = 5 \times 10^{10}$  G since the X-ray spectral fits of Cas A NS suggest  $B < 10^{11}\text{G}$  (Ho & Heinke 2009), and this NS is believed to be one of the several so-called central compact objects (CCOs) which have  $B \sim 10^{10} - 10^{11}\text{G}$  (Halpern & Gotthelf 2010; Ho 2011).

Following Yang et al. (2010), a moderately stiff equation of state (EOS) proposed by Prakash et al. (1988) is employed (model I). The maximum mass of this model is  $M = 1.977M_\odot$ , and the direct Urca process is forbidden in the case  $M < M_D = 1.36M_\odot$ . The relation between  $T_s$  and the internal NS temperature  $T$  is taken from Potekhin et al. (1997), which supposed the outer heat blanketing NS envelope is made of ion and neglected the effects of surface magnetic fields.

The cooling data of Cas A NS is taking from table 1 of Shternin et al. (2011). Mention that the effective surface temperature detected by a distant observer is  $T_s^\infty = T_s \sqrt{1 - R_g/R}$ ,

where  $R_g$  is the gravitational stellar radius. Since we mainly focus on the  $M = 1.361M_\odot$  neutron star model (the corresponding radius is 12.93 km),  $T_s^\infty = 0.83T_s$  is taken.

Fig.1 shows the cooling curves of neutron stars with different masses and fixed  $K=2$  ( $K$  is a free parameter describing the initial condition of the differential rotation). The plateaus of the curves indicate the heating effect due to  $r$ -mode dissipation, and the duration of this high temperature depends on the parameter  $K$  for selected neutron star mass (see Fig.3 of Yang et al. 2010). Since the direct Urca process begins to happen in the  $M = 1.36M_\odot$  neutron star model (which can greatly enhance the neutrino emission rate comparing with the modified Urca process), the cooling curves depend on the mass sensitively in the vicinity of it (see the curves of  $M = 1.361M_\odot, 1.362M_\odot, 1.365M_\odot$ ), and only the  $M = 1.361M_\odot$  curve passes through the region where the observed data located. Comparing to Fig.2 of Yu et al. (2009), one can easily find that the rapid cooling which can be used to explain the Cas A NS data occurs just after the completely shutoff of the  $r$ -mode heating process.

Fig.2 displays the cooling curves of the  $1.361M_\odot$  neutron star with different values of  $K$  and the curves are compared with the Cas A NS data. In comparison with the observations, the differential rotation parameter  $K$  can take the values around 2.0. In Fig.3 we plot our best fitted cooling curve ( $K=2.3$ ) in a larger span of ages and the curve without the  $r$ -mode heating effect is also displayed for comparison. An insert is also displayed to show the possible temperature drop in the following twenty years and the grey rectangle indicates the possible temperature scope predicted by the neutron-superfluidity-triggering model. It can be seen that the rapid cooling near the Cas A NS data will continue for several decades, and it will take a few hundred years to recover to the cooling rate of that not considering the  $r$ -mode heating effect. Although the behavior of the rapid cooling process of our model seems similar to neutron-superfluidity-triggering model (Page et al. 2011; Sheternin et al. 2011), they are different in detail. The part of the curve which best fits the observational data in both of their studies (see Fig.3 of Page et al. (2011) and Sheternin et al. (2011)) are closer to straight line than that of us. As a result, our best fitted curve predicts about 2% higher temperature in two decades (see the insert). Perhaps, this difference is distinguishable in future observations.

In fig.4, we plot the evolution of the amplitude of  $r$ -modes with the same parameters as fig.3. Abadie et al. (2010) analyzed the data of Cas A NS in a 12 day interval taken by LIGO, no gravitational-wave signal is found. But they gave the upper limits on the  $r$ -mode amplitude, which is 0.005-0.14. As far as our model is concerned, one can easily seen from fig.4 that the amplitude of  $r$ -modes has dropped to 0.005 about 24 years ago (that is the Year 1987). We also don't expect the gravitational-wave due to  $r$ -modes can be observed even by the advanced LIGO and Virgo interferometers, since the amplitude of  $r$ -modes has

declined to its initial value( $\alpha = 10^{-6}$ ) in 1997.

#### 4. Conclusions and discussions

Based on our former work about the  $r$ -mode heating effect of NS, we explained the rapid cooling of Cas A NS. When the  $r$ -mode heating process is switched off, the NS cools down rapidly, and it needs a few hundred years to recover to the normal cooling rate (which refers to the case that don't consider the  $r$ -mode heating effect). The rapid cooling as the Cas A NS occurs in the beginning of this recovery period and it will last for several decades. We also found that the behavior of our model and the neutron-superfluidity-triggering model has slight differences, and they might be distinguished by observations in the near future.

The essential element of our interpretation to the rapid cooling of Cas A NS is that the  $r$ -mode instable period of the star can last for about 300 years. Although many models about the nonlinear evolution of  $r$ -modes in NSs didn't expect such a long duration of  $r$ -mode instability(e.g., Rezzolla et al. 2001a,b; Bondaresu et al. 2009), some models did support it(e.g., Arras et al. 2003).

In our calculation, we assumed the outer heat blanketing NS envelope is made of ion. However, the Cas A NS is believed to have a carbon atmosphere (Ho & Heinke 2009). Theoretically, light elements make the envelope more heat transparent and the surface temperature of the same mass NS can be risen (Potekhin et al. 1997), and one has to explain the observations of the Cas A NS with the NS model of a little larger mass than  $1.361M_{\odot}$ .

What's more, we only considered a constant magnetic field in our simulation. Nevertheless, Rezzolla et al. (2001a,b) showed that the differential rotation induced by  $r$ -mode will generate a strong toroidal magnetic field, this could effect the  $r$ -mode evolution and should be taken into account in further work.

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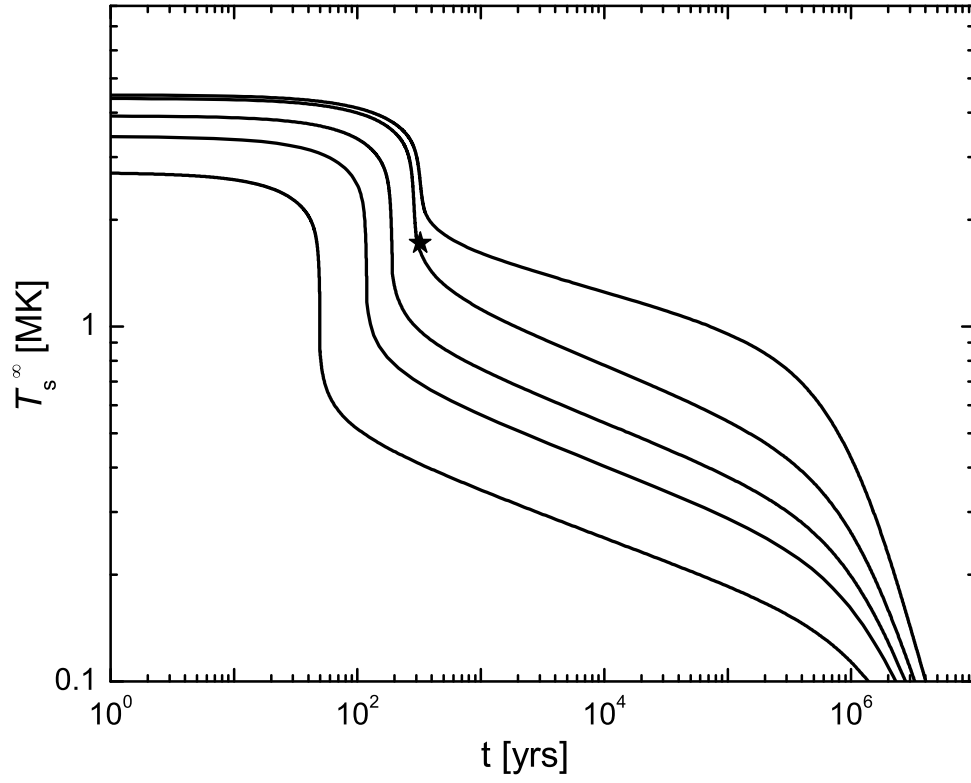


Fig. 1.— Cooling curves of neutron stars with  $K = 2$ . The curves correspond to the NS mass  $1.360M_{\odot}$ ,  $1.361M_{\odot}$ ,  $1.362M_{\odot}$ ,  $1.365M_{\odot}$  and  $1.4M_{\odot}$ , respectively. The pentagram presents the location of the observed cooling data of Cas A NS.



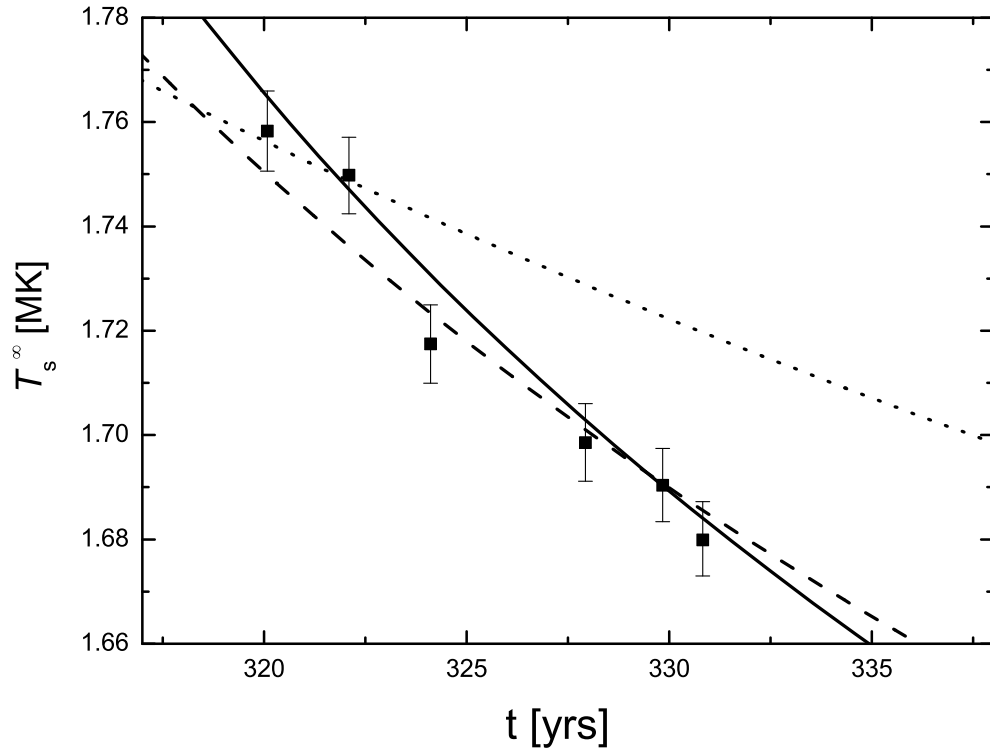


Fig. 2.— Cooling curves of the  $1.361M_{\odot}$  neutron star. The dot, dashed and solid curves correspond to  $K = 1.5$ ,  $K = 2.1$  and  $K = 2.3$ , respectively.

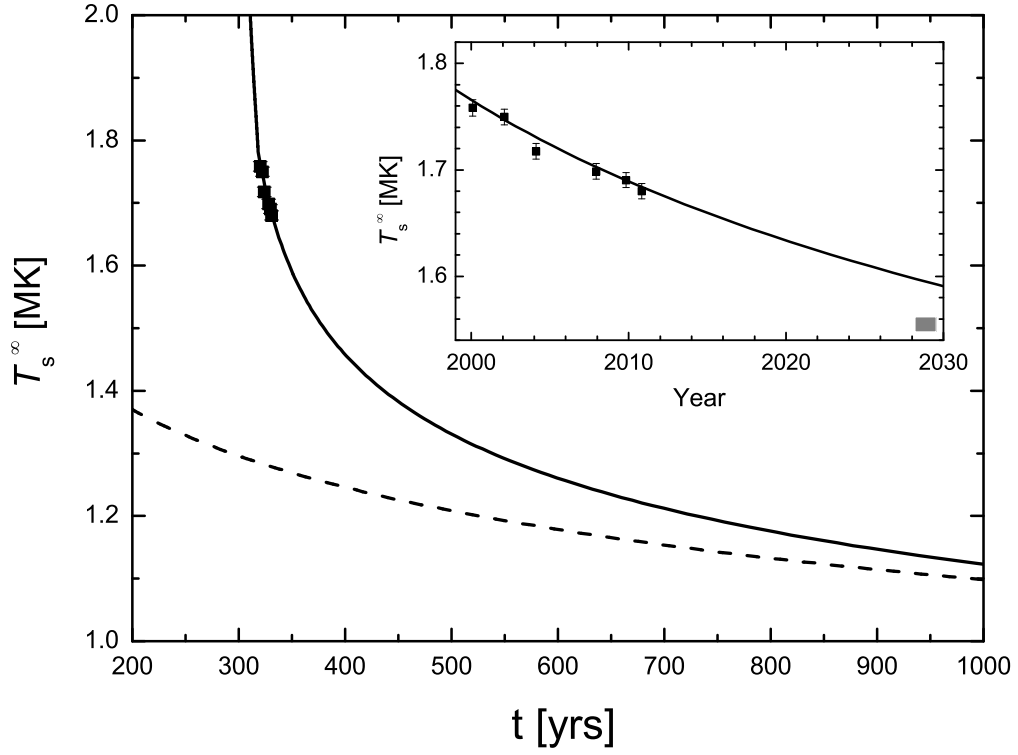


Fig. 3.— Cooling curves of the  $1.361M_\odot$  neutron star with  $K = 2.3$  (solid line). For comparison, the dashed line is calculated without the  $r$ -mode heating effect. The insert shows the temperature evolution in the following twenty years and the grey rectangle indicates the possible temperature scope predicted by the neutron-superfluidity-triggering model.

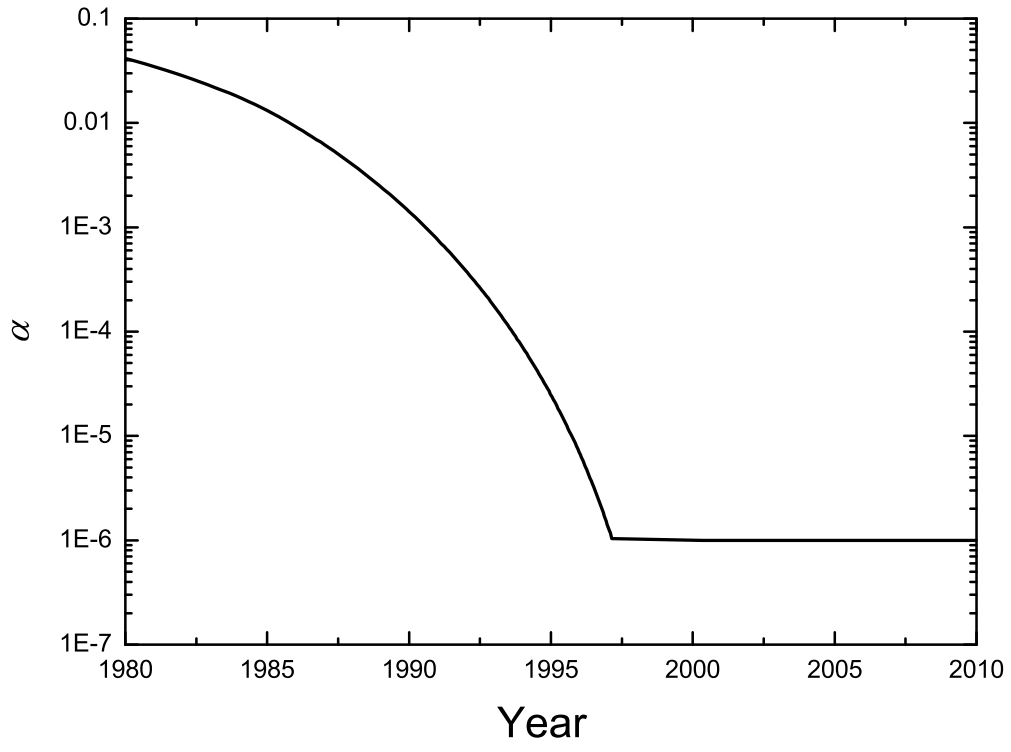


Fig. 4.— The evolution of the amplitude of r-modes of the  $1.361M_{\odot}$  neutron star with  $K = 2.3$ .